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Letter to the Editor

Life cycle environmental loads and economic efficiencies of apartment buildings built with plaster board drywall

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ABSTRACT

Due to the ease of remodeling apartment buildings, as well as the increased lifespans and performances required of apartment buildings, the demand for new plaster board drywall materials with outstanding flexibility is growing, and the importance of assessing the associated environmental load is increasing. This study evaluates the CO_2 generated during the life cycle of a building ($LCCO_2$) and its economic efficiency to assess the environmental loads and costs of buildings that use plaster board drywall.

A typical concrete bearing wall structure for an apartment building was defined as case 1, and comparisons were performed with alternative samples (cases 2, 3, and 4) containing different ratios of plaster board drywall on top of case 1. The structural safety of each sample building was considered along with the legal incentives according to the use of variable type wall. In addition, life cycle assessments of both CO_2 and economic efficiency were conducted according to stage, including the construction stage, operation/maintenance stage, and demolition/waste stage. Data including quantity of construction material, amount of energy usage, repair rate, and repair period (all of which are required during each stage of assessment) were utilized for the assessment of both CO_2 and economic efficiency.

As a result, in flat-type structures, the CO_2 reduction rates of cases 2, 3, and 4 compared to case 1 were 1.0%, 4.5%, and 5.4%, respectively. In the assessment of cost, the reduction rates compared to case 1 were −0.01%, 5.8%, and 6.0%, respectively. Also, in the tower-type structure, the CO_2 reduction rates of cases 2, 3, and 4 compared to case 1 were 1.3%, 4.9%, and 5.5%, respectively. In cost assessment, the reduction rates compared to case 1 were −1.1%, 3.3%, and 3.5%, respectively.

1. Introduction

1.1. Background and objectives

To foster sustainable development in the context of climatic changes, new agreements have been established including the Kyoto Protocol (1997), and demands for mandatory environmental load (hereafter CO_2) reductions in all industries have recently increased [1].

The construction industry is recognized as an environmentally hazardous industry, making up about 30% of CO_2 emissions in all industries, and thus requires research into sustainable practices to reduce CO_2 emissions. In particular, there are urgent demands for systematic and specific studies on methods of reducing CO_2 in diverse contexts, including analyses to reduce the amounts of construction materials used to build apartment buildings (which account for a considerable portion of CO_2 emissions), energy consumption, life span extension, and the application of new and renewable energy [2].

Sustainable building techniques are being developed in Korea to actively respond to climatic changes. However, as current information regarding the environmental impacts of different construction materials remains insufficient, comprehensive research on reducing CO_2 in construction materials is required. Studies to assess the life cycle CO_2 and cost of buildings using a significant database for construction materials are needed to facilitate sustainable qualitative growth in Korea.

Therefore, the objective of this study is to compare the life cycle CO_2 emissions and costs of construction for four different apartment buildings by defining an apartment building (*case 1*) as a standard, and three alternative buildings using plaster board drywall as comparison subjects (*case 2*, *case 3*, and *case 4*) to study the sustainable performance of buildings using different construction materials. Apartment buildings differ in terms of living units, number of floors, structure, and strength.

1.2. Methods

In this study, flat-type and tower-type standard apartment buildings were considered, and life cycle CO_2 emission amounts and costs were assessed for four different cases of apartment buildings depending on structural systems and adjusted ratios of plaster board drywall.

The structural safety of each case was assessed through structural analysis using MIDAS by varying the structural systems of both flat-type and tower-type standard apartment buildings and the ratios of applied plaster board drywall, and legal incentives were applied to apartment buildings that utilized plaster board drywall.

The life cycle CO_2 assessments of apartment buildings were divided into the construction, operation, maintenance, and demolition/waste stages, and the CO_2 emission amounts were assessed for each stage. The CO_2 emissions during the construction stage were assessed by considering the contributions of major CO_2 emitting materials during the construction stage. Energy consumption

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for the operation stage was assessed with the use of ECO-Designer, an energy simulation program associated with BIM, and the results were converted into amounts of CO_2. For maintenance stage assessment, CO_2 emissions were calculated based on repair period and repair rate, and the demolition/waste stage was assessed based on the energy required by different combinations of demolition equipment, transportation vehicles, and burial equipment.

Life cycle costs (LCC) were also assessed by dividing the life cycle into the construction, operation/maintenance, and demolition/waste stages. The construction stage was assessed using the elemental cost method based on the required amounts of energy estimated by ECO-Designer for the operation stage, the repair rate/repair period for the maintenance stage, and the amounts of wastes generated for the demolition/waste stage.

2. Literature review

2.1. Life cycle CO_2 of apartment buildings

Assessment of the life cycle CO_2 of a building comprises the quantitative assessment of energy consumption and CO_2 emissions that occurred during all stages of the life cycle of the building. To achieve such a quantitative assessment of the life cycle CO_2 of a building, the assessment range of each life cycle stage should first be identified, and then the CO_2 should be assessed for each stage [3].

The International Organization for Standardization (ISO) maintains the international standards (ISO 14040~43) for the assessment and calculation of life cycle CO_2, including the individual quantity survey method, industry association method, and combination method. The individual quantity survey method is used to estimate the amounts of emitted environmental load through a series of processes depending on the types and amounts of emitted materials. The industry association method calculates the amounts of energy consumed and environmental load of individual industrial sectors, among a total of 405 industrial sectors. The combination method is effective for subjects that combine products such as building energy and environmental load [4].

Assessment programs of the entire construction process that follow these guidelines have been developed in Korea and other countries. Available programs in Korea include the SUSB-LCA program, which assesses energy consumption and CO_2 emissions according to construction stage, the TOTAL program, which was developed using the national lifecycle inventory (LCI) database, and the PASS LCA program of the Korea Accreditation Board. In other countries, the Carbon Navigator program of Japan can review CO_2 reduction during the initial stage of planning, the BASIX program of Australia can assessCO_2 reduction using a simple checklist method, and LISA of Australia and ENVEST2 of the U.K. are already developed. Although such diverse assessment programs are already on the market, data regarding the costs associated with construction materials are still insufficient, and it is therefore difficult to consider the LCC of apartment buildings. Therefore, research on construction materials is still required [5–7].

2.2. The life cycle costs of apartment buildings

LCC include the sums of all costs incurred during the construction, operation, maintenance, and scrap stages. The majority of construction companies in Korea assess apartment building costs based on standard estimates and unit prices. The Korea Ministry of Land, Transport, and Maritime Affairs and the Korea Institute of Construction Technology recently advocated the estimation of construction costs utilizing price data in order to avoid quoting construction costs using standard estimates. Some studies have emphasized the importance of incorporating price data, while criticizing standard estimates as not only incapable of reflecting frequently changing market prices, but also limited in accommodating new technology and construction methods. However, the use of actual price information is not widely practiced by Korean construction companies, and cost assessments of most construction projects are still produced based on standard estimate and unit prices [8].

The elemental cost method and elemental unit quantity method remain in use to assess costs in Korea and other countries. The elemental cost method calculates the construction costs per unit area based on gross area. The elemental unit quantity method calculates the required costs of materials by calculating the quantity of materials required for each building and multiplying the unit price of each material. These methods are similar to the standard estimate, unit price and price data methods used in Korea [9–11].

2.3. Sub-conclusion

In this study, we assessed the life cycle CO_2 of apartment buildings using the SUSB-LCA assessment program by classifying the life cycle into the construction, operation/maintenance, and demolition/waste stages. In the assessment of LCC, the standard estimate and unit price methods were used by classifying the life cycle into the construction, operation/maintenance, and demolition/waste stages based on the elemental cost method.

3. Selection of the apartment buildings to be assessed

3.1. Overview

In the assessment of the life cycle CO_2 and building costs, a typical concrete wall structure was selected as case 1 (standard apartment building). Table 1 shows an overview of case 1.

Table 1
The overview of standard building.

Flat type apartment	Tower type apartment
Exclusive area: 84.95 m^2	Exclusive area: 84.97 m^2
No. units: 4/floor	No. units: 4/floor
Supply area: 33 pyeong (111.33 m^2)	Supply area: 33 pyeong (109.49 m^2)
Structure: concrete wall	Structure: concrete wall
Strength: whole floor 24 MPa	Strength: whole floor 24 MPa
Stories no.: above ground 25 stories	Stories no.: above ground 25 stories

Based on the structural system and the ratio of plaster board drywall on top of case 1, case 2, case 3, and case 4 were developed as shown in Table 2. Flexibility, structural validity, and safety were considered while selecting the wall systems for the buildings built using plaster board drywall. In addition, legal incentives for the use of flexible walls in each case were considered.

3.2. Items of assessment

In this study cases were classified according to the method and location of plaster board dry walls. Also, the structural safety of the buildings was assessed by structural analysis. In addition, the legal incentives for the floor area ratios for flexible walls were analyzed.

Table 2
Cases of buildings that applied plaster board drywall.

Cases	Structure	Contents
Case 1	Wall structure	Standard building
Case 2	Wall structure	Bearing walls within household, and column length ratio is below 40–70%
Case 3	Wall type + column type (mixed structure)	Bearing walls within household, and column length ratio is below 10–40%
Case 4	Column type (flat slab structure)	Bearing walls within household, and column length ratio is below 10%

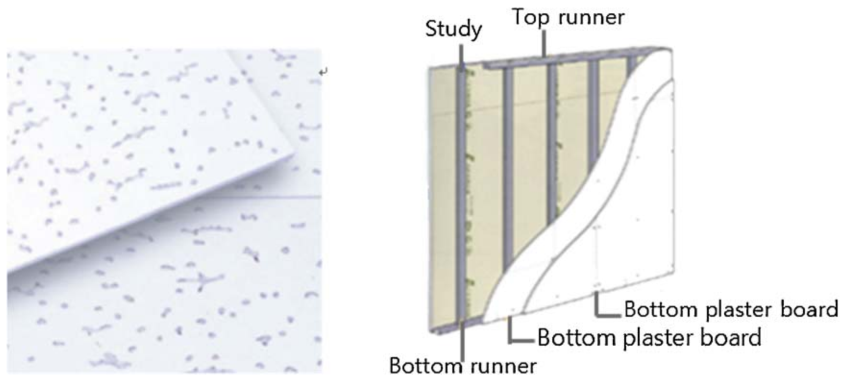

Fig. 1. Single stud partition system.

3.2.1. Analysis of plaster board drywall

Before the concrete wall structure was modified to the plaster board drywall, plaster board was classified into single stud partition, bearing wall finish, and ceiling finish depending on the location and purpose of the plaster board used for analysis.

The single stud partition system walls between households were composed of 2 folds of plaster board (12.5T), C-Stud, glass face (24K 50T), and 2 folds of plaster board as shown in Fig. 1. Unit prices are shown in Table 3. The Gyp bond running method was applied to finish bearing walls (9.5T), and wood ceiling frames were applied in the plaster board ceiling finish method for the ceiling system (9.5T) [12].

3.2.2. The assessment of structural safety

In this study, an existing bearing wall was replaced with a flexible wall to assess structural safety along with the flexibility of the building according to each case.

A series of comprehensive structural analyses were conducted to ensure structural safety in cases 2, 3, and 4, since their structural systems and wall compositions were modified.

MIDAS ADS (ver.2.2.2) was used for structural analyses with models for both flat-type and tower-type structures. The designs of each structure were in compliance with KBC2009, the structural design standard of Korea, and satisfied KBC2009 requirements such as horizontal displacement against wind load, seismic load and the rule on inter-story displacement, while structural safety was secured through calculations of the load combinations applied to all loads on the structures. The structural design of each case applied the same analytical process from case 1 (a concrete wall structure) to case 4 (a flat slab structure). In addition, a vertical dead load (including a finishing load) and live load were applied, and a horizontal wind load and seismic load were applied.

Table 3
Single stud partition system unit price.

Material	Size	Unit	Q'ty/m^2
General plaster board	12.5 × 900 × 2400	m^2	4.20
C-Stud	50 × 45 × 0.8T	m	2.45
C-Runner	52 × 45 × 0.8T		0.87
Pin (for runner fixing)	NK-27	EA	1.56
Screw nail for plaster board	Φ3.5 × 25	EA	20.42
	Φ3.5 × 40	EA	38.89
Insulator fixing pin	50 type	EA	14.58
Glass face	24K 50T		1.05
Joint tape	Net type	m^2	2.10
Joint compound	Ready-mix type	kg	1.05
General sealant	–	L	0.11

3.2.3. Legal incentives for the use of flexible wall

Legal incentives by using a flexible wall for floor area ratio related incentives were analyzed in cases 2, 3, and 4. Article 8 (special case of remodeling) of the Building Act of the Korea Ministry of Land, Transport, and Maritime Affairs and relevant law provisions require that an incentive of a floor area ratio of 10% is granted when the assessed score is 80 points or above as a result of screening by the construction committee, and the city of Seoul grants incentives on floor area ratios when the assessment score by the Housing Department of Seoul is 80 points or above, according to provisions for sustainable apartment buildings.

Table 4 shows the results of analysis for the assessment of legal incentives for flat-type and tower-type buildings. The results indicate that while case 2 would not earn incentives, case 3 is eligible for 10% incentive if the building is scored "B" or above, which is equivalent to 80 points on the separation of structure and MEP system by receiving 30 points on structure-type items and 17 points on flexible unit plan items. Case 4 is eligible for a 10% incentive if the building is scored "B" or above, which is equivalent to 80 points on the separation of structure and MEP system items with 37 points on structure-type items and 20 points on flexible unit plan items.

3.3. Assessment result

Walls that fall under the categories of each case were selected as shown in Figs. 2–4 with the use of the BIM model based on structural safety, and due to the floor area ratio incentives on the use of the flexible wall, cases 3 and 4 showed increases of 2 floors. In addition, cases 3 and 4 showed decreases in floor height due to their inclusion of the flat slab structure; thus, 1 additional floor is achieved. The results of incentive analysis are shown in Table 5.

4. Assessment of the life cycle CO_2 of building using plaster board drywall

4.1. Overview

In this study, buildings were classified into case 1, case 2, case 3, and case 4 for the assessment of lifecycle CO_2, and the CO_2 amounts were assessed by stages, including the construction stage, operation/maintenance stage, and demolition/waste stage [13–15].

4.2. Construction stage

The construction stage was further divided into the material production stage, material transport stage, and building construction stage. In particular, in the material production stage, MIDAS and BIM models for each case were developed to estimate the quan-

Table 4
Assessment indicators for apartments that can be easily remodeled.

Assessed Items	Assessment criteria	Score	Case 1	Case 2	Case 3	Case 4	
1. Dwelling unit flexibility	Structure type	A. RC structure	38–40	■	■	■	■
		B. Flat Slab structure	33–37	■	■	■	37
		C. Mixed structure	28–30	■	■	30	■
2. Separation of structure and MEP	Separation of dedicated MEP	A. Design separate space for piping + wiring within dwelling unit.	18–20	■	■	■	■
		B. Design separate space for wiring within dwelling unit.	13–17	■	■	17	17
	Separation of common use MEP	A. Located at communal space or outside of main building for easy maintenance + reserve extra shaft space.	18–20	■	■	■	■
		B. Located at communal space or outside part of main building for easy maintenance.	13–17	■	■	17	17
3. Inside dwelling unit flexibility	The ratio of the bearing wall and column lengths within the household	A. Less than 10% ratio of bearing wall inside the household and length of column.	18–20	■	■	■	20
		B. Over 10% and less than 40% ratio of bearing wall inside the household and length of column.	13–17	■	■	17	■
		C. Over 40% and less than 70% ratio of bearing wall inside the household and length of column.	8–12	■	12	■	■
4.Environment friendliness	Noise, vibration, sound insulation, energy saving, indoor air quality etc.	A. Applied standards that are decided by the related legislation.	Requisite	○	○	○	○
	Sum				12	81	91

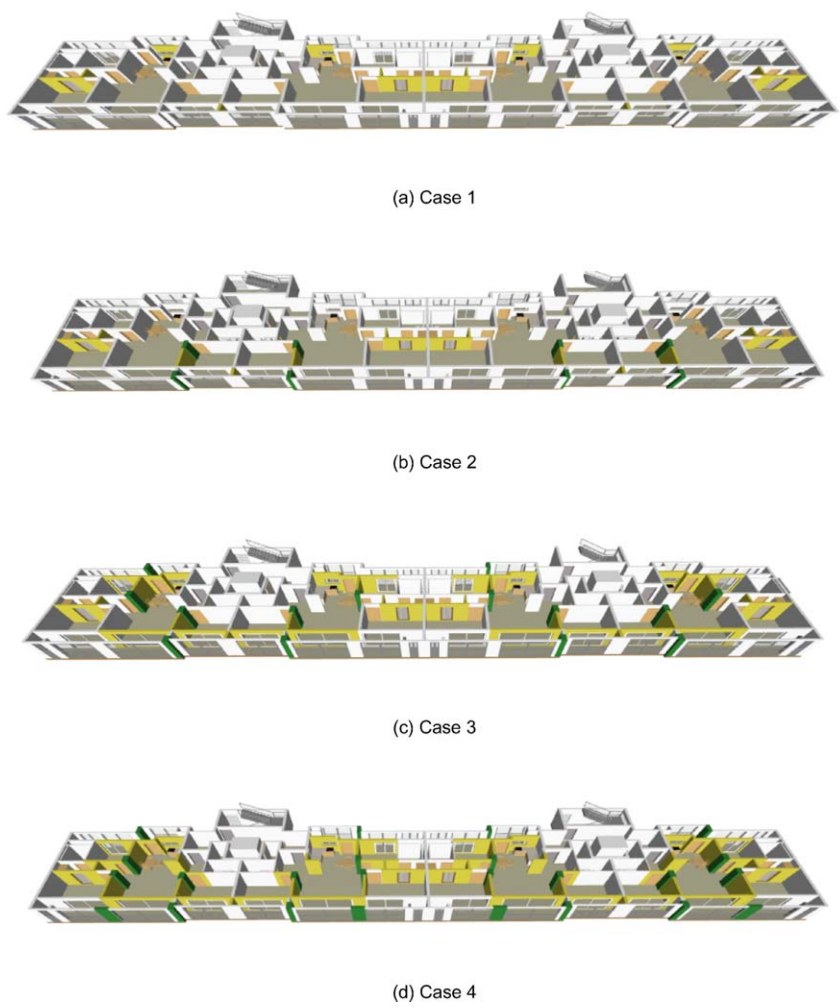

Fig. 2. Cases of BIM model for flat type.

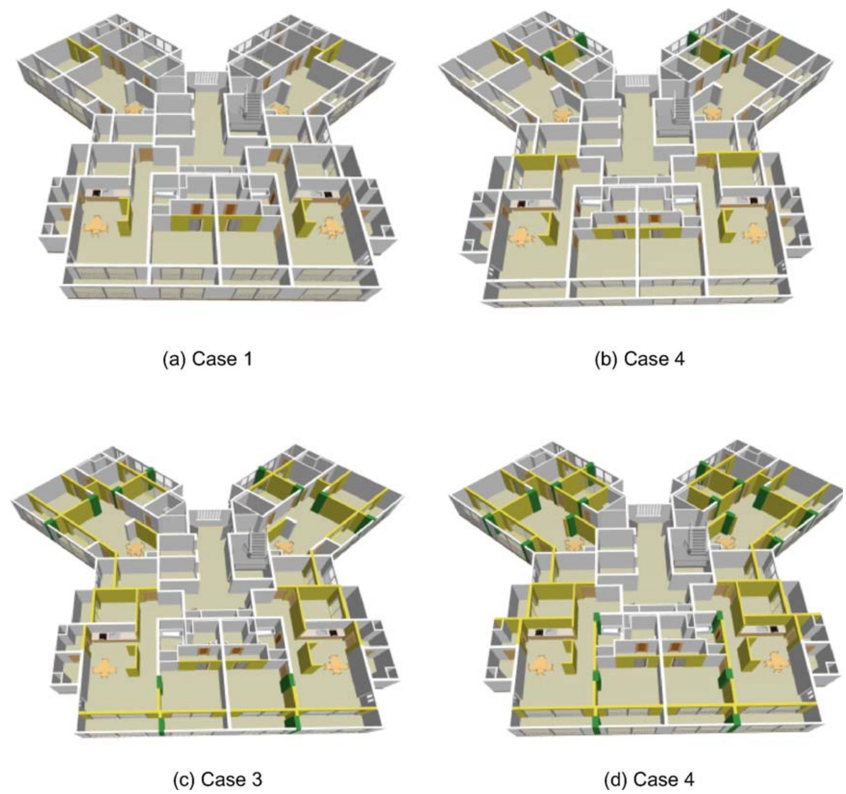

Fig. 3. Cases of BIM model for tower type.

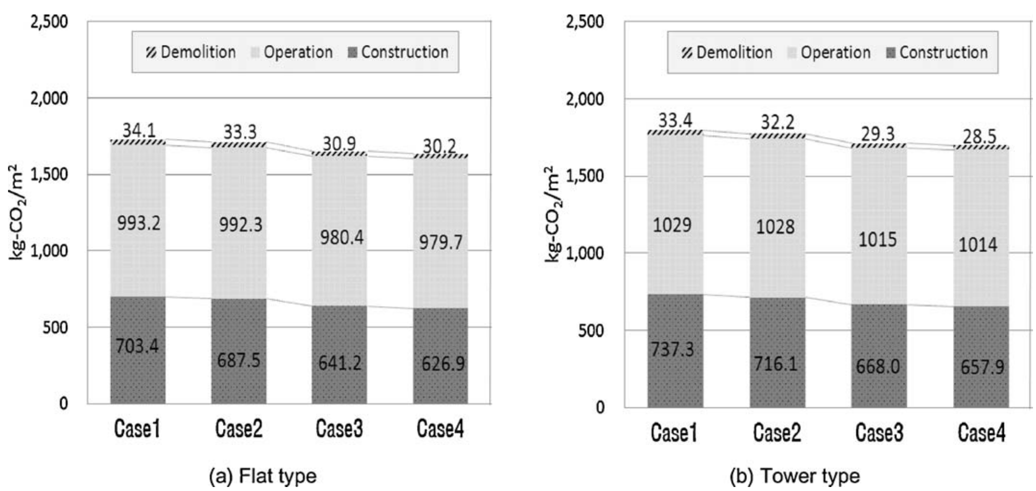

Fig. 4. The results of lifecycle CO_2 assessment.

tity of major materials based on existing research, and the data of each case were deduced through the quantity estimation of plaster board for flexible type apartment buildings to enable CO_2 assessment.

4.2.1. Material production stage

(1) Calculating structural quantity using MIDAS

Structures were analyzed by MIDAS to review structures by cases and determine the proper member size, and structural

Table 5
Summary of legal incentive analysis results.

	Case 1		Case 2		Case 3		Case 4	
	Flat type	Tower type	Tower type	Tower type	Flat type	Tower type	Flat type	Tower type
Dedicated area (m^2)	84.95	84.97	84.95	84.95	84.95	84.95	84.95	84.95
Supply area (m^2)	111.38	108.41	111.38	108.41	111.38	108.41	111.38	108.41
Structure type	Wall type	Wall type	Wall type	Wall type	Mixed type	Mixed type	Mush-room structure	Mush-room structure
No. of floors	25	25	25	25	28	28	28	28
Entire gross area (m^2)	8495.0	8497.0	8495.0	8497.0	9514.4	9516.6	9514.4	9516.6

Table 6
The results of calculating quantities for flat type and tower type.

		Dedicated Area (m^2)	Concrete (m^3/m^2)	Rebar (ton/m^2)	Model (m^2/m^2)
Case 1	Flat type	8495.00	0.84	37.31	51.54
	Tower type	8497.00	0.81	37.67	53.92
Case 2	Flat type	8495.00	0.81	40.56	50.77
	Tower type	8497.00	0.78	36.95	53.01
Case 3	Flat type	9514.40	0.76	42.07	47.76
	Tower type	9516.60	0.71	38.39	52.65
Case 4	Flat type	9514.40	0.74	45.33	47.54
	Tower type	9516.60	0.69	42.20	52.62

Table 7
The areas (m^2) of used walls of plaster board (12.5T) by case.

	Case 1		Case 2		Case 3		Case 4	
	Flat type	Tower type	Flat type	Tower type	Flat type	Tower type	Flat type	Tower type
Plaster board length (m)	14.68	16.43	23.62	27.91	48.48	66.01	60.32	78.57
No. of stories	25.00	25.00	25.00	25.00	28.00	28.00	28.00	28.00
Floor height (m)	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
Area (m^2)	880.80	985.68	1417.20	1674.36	3257.86	4436.14	4053.50	5280.04

quantities of concrete, rebar, and mold by each case were calculated as shown Table 6.

(2) Calculating finishing materials quantity using BIM

Based on the size of structural members determined by structural analysis and "The Legal Incentives on the Use of Flexible Type Wall", which is described in Section 3, a set of BIM-models were created with Archi CAD 10 for cases 1 and 2 (set as 25 stories) and cases 3 and 4 (set as 28 stories).

In addition, based on the detailed BIM model and the structure quantities estimated previously, the finishing area and material quantity were calculated for each case. A total of 81 material quantities were calculated by applying the unit price [16].

(3) Calculating the plaster board quantity of flexible type apartment buildings

Plaster board walls were classified according to information on the finishing area calculated in the BIM-modeled drawing and the type of partition, finishing, and ceiling. The areas of general wall plaster board (12.5T), finishing material plaster board (9.5T), and ceiling material plaster board were calculated as shown in Tables 7 and 8. In addition, in order to deduce the amount of plaster board from the calculated finishing materials of plaster board for all of the cases, the quantities of plaster boards and relevant materials were calculated based on the unit prices of Table 3 described in chapter 3.

(4) Calculation of CO_2 in material production stage.

The CO_2 emissions from the major CO_2 emitting materials in the material production stage were calculated based on the construction materials CO_2 unit DBs from the 2003 Inter-industry Analysis and national LCI DB mixed method for the major materials that emit CO_2 in building constructions for each case described above [17,18].

Specifically, the amounts of CO_2 were calculated by the sums of the CO_2 emissions from building constructions and those of civil constructions, where the CO_2 of building constructions were calculated by assigning weights of all the construction materials to the amount of CO_2 (80% of building construction materials production stage) of major materials calculated above. The amounts of CO_2 for the MEP system and civil constructions were then calculated by applying environmental load ratios (building construction 85.3%, equipment construction 12.0% and civil construction 2.7%) of each construction type obtained in existing research to the CO_2 emission amounts calculated in building construction [19,20].

4.2.2. *Material transport stage*

The CO_2 generated during the construction materials transport stage can be calculated based on the methods of transport or transport distance by materials and the types of fuel and electric power consumed in transport. The materials transport stage in this study (a stage intended for the estimation of virtual building) was calculated on CO_2 based on the numerical expressions of existing study materials, assuming that the materials storage warehouse and building construction field are 30 km apart.

4.2.3. *Building construction stage*

In this stage, where construction conditions in each field use different construction methods and equipment, as in the materials transport stage, the CO_2 emission amounts for each case were calculated by setting the numerical expression (based on bearing wall type) of existing research data as a reference value for the calculation of the estimated value for virtual building. In order to utilize the reference values of existing research data, the reference values of the initial supply area were converted to the values of the dedicated area based on case 2 data for each type, and the CO_2 for each case was calculated. In addition, since the amount of energy induced during construction differs depending on the amount of concrete used as a main construction material (even if dedicated area is the same), the CO_2 of the building construction stage for each case was calculated by applying the concrete consumption rate [21].

Table 8
The areas (m^2) of finishing walls of plaster board (9.5T) by case.

	Case 1		Case 2		Case 3		Case 4	
	Flat type	Tower type	Flat type	Tower type	Flat type	Tower type	Flat type	Tower type
Plaster board length (m)	165.42	121.05	139.54	101.93	98.62	43.55	42.49	23.63
No. of stories	25.00	25.00	25.00	25.00	28.00	28.00	28.00	28.00
Floor height (m)	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
Area (m^2)	9,925.44	7,263.12	8,372.64	6,115.92	6,627.53	2,926.56	2,855.26	1,587.94

Table 9
The reference values for the operation stage of each building.

Assessed Item	Flat Type	Tower Type
Sunlight condition	No shield, no blind	Many shields, and no blind
Envelope deflection degree	Plain	Many deflections
Glass and doors & windows	Heat exchanging insulator applied, multi-layer glass with 6 mm air layer (low-E), heat exchange flow rate 3.1 W/m^2·K	

4.3. Operation and maintenance stage

The operation stage, which generates the largest amount of energy consumption and CO_2 emission during the life cycle of a building in general, can be divided broadly into the building using stage where residents use energy within the building and maintenance stage [22].

4.3.1. Operation stage

In this study the patterns of energy consumption in the operation stage were assessed with the use of ECO-Designer, computer simulation software utilizing a BIM model based on the virtual building climatic environment. Since the assessment method differs depending on the climatic environment and heating method, the values for all the cases were assessed based on the same conditions. Table 9 shows the reference values for the operation stage of the buildings assessed in this study [23].

4.3.2. Maintenance stage

In this stage CO_2 was analyzed according to the repair period and repair rate method only for plaster board and paints as materials of major repair subjects, and the data on the repair period and repair rate were assessed based on "The Long Term Repair Plan" from Table 5 of Article 30 Establishment Standard of Section 1 of Article 26 of the Housing Act Enforcement Rule [24].

4.4. Demolition and waste stage

The building demolition and waste stage is the stage during which the building lifespan comes to an end, the structure is demolished, and construction wastes are produced, and can be classified broadly into the building demolition stage, wastes transport stage, and waste burial stage. In this study the demolition and waste stage was assessed by the amount of energy used by the combination of scrap equipment, transport vehicle selection method, and burial equipment [25].

4.4.1. Demolition stage

To calculate the amount of waste generated during the demolition stage, the estimated amount of waste in the 2010 building construction standard estimate building section wastes management standard was set as a reference value, and the amount of CO_2 based on the dedicated areas for each case was calculated.

Since the amount of waste generated varies depending on the structure type and the amount of concrete/rebar induced even if dedicated area, the concrete induced ratio was applied, and the CO_2 of the demolition stage for each case was calculated assuming that the Backhoe (1.0 m^3) + Giant Breaker (0.7 m^3) were induced during the building demolition stage.

4.4.2. Wastes transport stage

The waste transport stage can be assessed according to the CO_2 emitted from the equipment that transports wastes from the building demolition field to the landfill.

In this study the waste transport stage was assessed under the assumption that the distance from the building dismantle field to the landfill is 30 km, and the used transport vehicle is a 20 ton dump truck (with a fuel consumption rate of 2.33 km/l) in all cases.

4.4.3. Wastes burial stage

The waste burial stage is the stage during which the wastes generated by the building demolition stage are buried. This stage is assessed with the CO_2 emitted by the use of burial equipment, and in this study the CO_2 from each case was calculated assuming that the burial equipment types were a dozer and compacter (with fuel consumption ratios of 0.15 l/ton).

4.5. Assessment result

Table 10 shows the results of the assessment of CO_2 for the life cycle of buildings. According to the table for flat type buildings, compared with case 1, cases 2, 3, and 4 showed reductions of 1.0%, 4.5%, and 5.4%, respectively, and in the construction stage they showed reductions of 2.3%, 8.8%, and 11.0%, respectively.

For tower type buildings, compared with case 1, cases 2, 3, and 4 showed reductions of 1.3%, 4.9%, and 5.5% in the life cycle CO_2 assessment, respectively, and in the construction stage they showed reductions of 2.9%, 9.4%, and 10.8%. Such results may occur because the quantities of concrete and rebar per unit area decreased as the wall type structure of case 1 was modified to a column type structure and the existing bearing wall was replaced with plaster board drywall.

Table 10
The results of building life cycle CO_2 assessment.

Building life cycle		Case 1		Case 2		Case 3		Case 4	
		Flat type	Tower type	Flat type	Tower type	Flat type	Tower type	Flat type	Tower type
Construction stage	Material production	641.15	676.23	626.61	656.92	584.15	613.53	570.95	604.77
	Material transport	7.40	7.04	7.40	7.04	7.40	7.04	7.40	7.04
	Material construction	54.88	53.69	53.53	51.78	49.67	47.04	48.61	45.77
	Sub-total	703.43	737.31	687.54	716.09	641.22	667.98	626.96	657.93
Operation/maintenance stage	Operation	955.00	993.52	955.00	993.52	945.63	983.77	945.63	983.77
	Maintenance	38.29	35.82	37.37	34.61	37.37	31.61	34.07	30.80
	Sub-total	993.29	1029.34	992.37	1028.13	980.42	1015.38	979.70	1014.57
Demolition/waste stage	Demolition	29.07	28.43	28.35	27.42	26.30	24.91	25.75	24.24
	Waste	4.37	4.27	4.26	4.12	3.95	3.74	3.87	3.64
	Transport	0.76	0.74	0.74	0.72	0.69	0.65	0.67	0.63
	Sub-total	34.19	33.45	33.35	32.26	30.94	29.31	30.29	28.51
	Total	1730.9	1800.1	1713.26	1776.5	1652.6	1712.7	1637.0	1701.0

Unit: kg-CO_2/m^2.

Table 11
The results of cost analysis by case.

Cost analysis by cases		Case 1		Case 2		Case 3		Case 4	
		Flat type	Tower type	Flat type	Tower type	Flat type	Tower type	Flat type	Tower type
I. Building construction	1. Installation work	6015	6015	6015	6015	6015	6015	6015	6015
	2. Foundation work	956	956	956	956	956	956	956	956
	3. Rebar work	115,561	123,916	117,868	121,606	111,713	119,706	115,908	123,731
	4. Bricks & masonry work	5541	19,364	5390	19,364	4432	11,997	4276	11,997
	5. Waterproof work	11,660	11,660	11,660	11,660	11,660	11,660	11,660	11,660
	6. Plaster work	29,378	29,378	29,378	29,378	29,378	29,378	29,378	29,378
	7. Tile work	27,963	27,963	27,963	27,963	27,963	27,963	27,963	27,963
	8. Masonry work	9601	9601	9601	9601	9601	9601	9601	9601
	9. Interior finishing work	39,105	39,105	38,790	38,790	38,732	38,732	38,582	38,582
	10. Wallpaper work	11,451	9847	11,143	9777	9190	10,416	8872	10,198
	11. Doors & windows work	43,652	52,383	43,652	52,383	43,652	52,383	43,652	52,383
	12. Glass work	8213	9856	8213	9856	8213	9856	8213	9856
	13. Painting work	5150	5696	5010	5561	4119	4738	3975	4666
	14. Furniture work	68,875	68,875	68,875	68,875	68,875	68,875	68,875	68,875
	15. Metal work	7752	7752	7752	7752	7752	7752	7752	7752
	16. Miscellaneous work	5150	5150	5150	5150	5150	5150	5150	5150
	II. Electric work	82,998	85,488	82,998	82,998	82,998	82,998	82,998	82,998
	III. Equipment installation	95,789	98,663	95,789	95,789	95,789	95,789	95,789	95,789
	IV. Landscape work	10,276	10,584	10,276	10,276	9175	9175	9175	9175
	Total	585,087	622,252	586,479	613,750	575,364	603,140	578,792	606,726
Ratio of construction cost over case 1 (%)		100	100	100.2	98.6	98.3	96.9	98.9	97.5

Unit: won/m^2.

5. The assessment of the life cycle cost of buildings using plaster board drywall

5.1. Overview

In this study buildings were classified as case 1 as a reference building and cases 2, 3, and 4 to assess the LCC of buildings. The life cycle of a building was categorized into the construction stage, operation/maintenance stage, and demolition/waste stage, and the life cycle CO_2 deduced above was reflected to assess the LCCs of buildings [26].

5.2. Construction stage

In this study the construction stage was assessed by further division into direct construction cost assessment and the cost calibration stage, depending on whether the construction period increased or decreased. The direct construction costs in the construction stage were calculated by calculating quantities and composition of design drawing for major construction types. As for the other construction types, the construction costs per unit area by construction types were calculated by utilizing the achievement data of similar constructions, and the required costs were calculated by multiplying them by the construction gross area. The stage during which costs were calibrated was analyzed quantitatively depending on whether the construction period increased or decreased through simulation of construction periods by case [27,28].

5.2.1. The assessment of direct construction cost

The characteristics of building construction vary in construction methods, construction materials, and the productivity of the induced workforce for each project. Thus, construction costs may differ slightly even for identical projects. Therefore, since cost calculating conditions and assumptions should be established clearly before the calculation of construction cost, the conditions of construction cost calculation in this study are provided as follows.

First, only the direct construction cost for one building of 25 stories with 4 units per floor was calculated, where subsidiary facilities, overheads, and other costs were excluded. Second, construction costs were calculated by unit price after the calculation of elemental cost and elemental quantity, and other construction types were assessed by taking arithmetic means of 3 similar estimated construction prices. However, for past construction cost calculation time points, the inflation rate was estimated by utilizing “Building Construction Cost Indices” from the Korea Institute of Construction Technology. Lastly, the costs incurred by the difficult degree of construction in concrete wall type structures and flat slab structures were not reflected.

In the calculation of flat type construction costs, reinforced concrete construction, brick and masonry work, interior finishing work, wallpapering work, and painting work were calculated based on drawing and unit prices, and the supporting work, foundation work, waterproof, tile, masonry, furniture, metal, and miscellaneous constructions were calculated based on the costs by converting the achievement data of similar constructions.

As for the construction cost of tower-type structures, case 2 was similar to case 1, and cases 3 and 4 showed reduction of the framework construction quantity per unit area. In addition, cases 3 and 4 showed reduction of bricks and masonry work. Interior finishing work, wallpaper work, and painting work all showed reductions of construction cost per unit area due to the reduction of quantity toward case 4. Table 11 shows the results of cost analysis on flat-type and tower-type structures for each case.

5.2.2. Calibration of cost by the increase and decrease of construction period

Building construction costs fluctuate depending on the construction period, so for accurate cost analysis, the contents of the construction period also need to be reflected in the costs. Therefore, in this study the periods were analyzed quantitatively through simulation of the construction period for each case, and the calibration results in Table 12 were obtained. As for the conditions of the construction period simulation, one building of 4 households combined as an apartment was simulated, and only critical activities were considered. Critical activity is any activity that determines

Table 12
Calibration of costs by the increase and decrease of construction period.

Class	Case 1		Case 2		Case 3		Case 4	
	Flat type	Tower type	Flat type	Tower type	Flat type	Tower type	Flat type	Tower type
Construction period (days)	780	780	770	770	735	735	670	670
Increase and decrease (compared with case 1)	■		10 days (decrease) (0.3 months)		45 days (decrease) (1.5 months)		190 decrease) (3.6 months)	
Construction cost reduction amount (won/m^2)	■	■	753.4	753.2	3,373.9	3,373.0	8,093.0	8,091.1
After deduction of reduced amount (won/m^2)	585,087	622,252	585,725	612,997	571,990	599,766	570,698	598,633
Ratio (%) of construction cost over case 1	100	100	100.1	98.5	97.8	96.4	97.5	96.2

Table 13
The results of life cycle cost assessment.

Building life cycle		Case 1		Case 2		Case 3		Case 4	
		Flat type	Tower type	Flat type	Tower type	Flat type	Tower type	Flat type	Tower type
	Construction stage	614,341	653,365	615,803	643,647	604,133	629,755	607,731	628,565
Operation/maintenance stage	Operation	11, 88	11,994	11,531	11,600	9706	9631	9573	9397
	Maintenance	316, 461	340,259	316,461	340,259	279,580	334,961	279,580	334,961
	Sub-total	317, 649	352,253	327,992	351,859	289,286	344,592	289,153	344,358
	Waste stage	1319	1315	1319	1315	1319	1315	1319	1315
	Lifecycle CO_2	0	0	−426	−571	−1892	−2112	−2269	−2393
	Total	944,009	1,006,933	943,897	996,250	889,303	973,550	887,437	971,845

Unit: won/m^2.

the entire construction period, and thus means the longest path in the process table. In addition, as for the number of days spent for the process simulation, working days excluding holidays and non-working days were used [29,30].

5.3. Operation stage

Similar to the assessment of the life cycle CO_2 of buildings, costs were calculated for each case based on the amounts of electricity and natural gas used with ECO-Designer, an add-on software program within Archi-CAD. Among annual energy costs, the electricity unit price was applied as 80 won (kWh/won), and the heating gas unit price was applied as 720 won (m^3/won) for the calculation. Maintenance costs were calculated with the use of maintenance quantity by reflecting plaster board and paint repair rates and repair periods.

5.4. Waste stage

To calculate the processing cost after deducing the construction waste amounts for each case, the amounts of generated waste were calculated from the generated waste unit amount with the use of existing data from the Seoul City Administration Development Institution.

5.5. Assessment results

The results of the LCC assessment for each case are shown in Table 13, and in this study the results of the life cycle CO_2 assessed

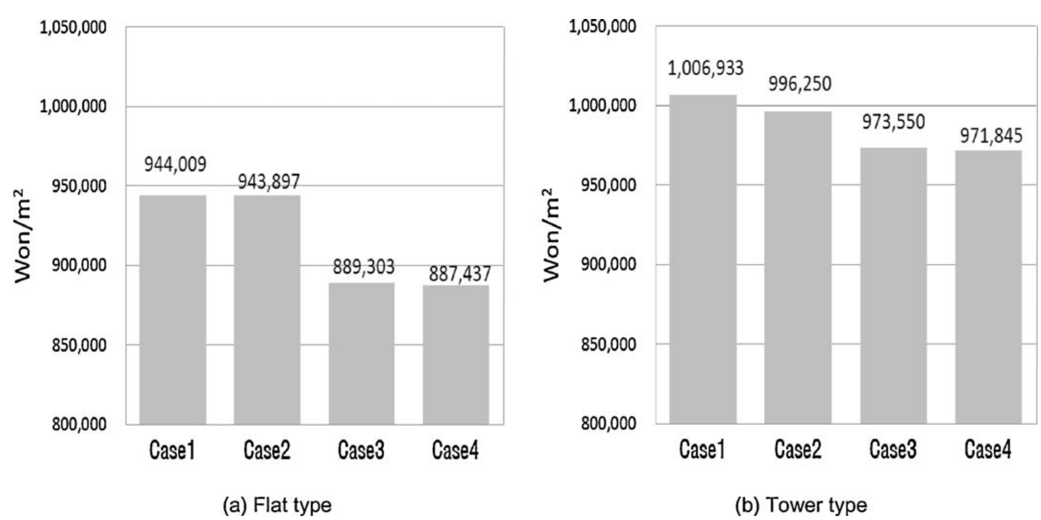

Fig. 5. The results of lifecycle cost assessment.

in Section 4 were reflected in the cost assessment. For conversion to cost, European carbon emission trading quotations (€13.37, 20,955 won) were applied, and with case 1 taken as a reference, the amounts reduced in cases 2, 3, and 4 compared with case 1 were expressed.

The results of the assessment of LCC of flat-type buildings indicated that compared with case 1, case 2 increased by 0.01%, case 3 decreased by 5.80%, and case 4 decreased by 5.99%, where cases 3 and 4 were shown to be economical compared with case 1. Tower-type assessment results indicated that compared with case 1, case 2 decreased by 1.06%, case 3 by 3.32%, and case 4 by 3.48%, and led to the conclusion that cases 2, 3, and 4 all were economical compared with case 1. Furthermore, the results of the LCCs assessment showed that the flat type provided greater cost reduction than the tower type (Fig. 5).

6. Conclusions

This study was conducted to assess the life cycle CO_2 and costs of buildings using plaster board drywall to determine sustainable building practices, and reached the following conclusions.

1. As a result of analyzing the legal incentives to the use of flexible type walls in the buildings, an additional 10% of floor area could be applied to case 3 and case 4 by the use of the flexible type wall using plaster board drywall.
2. As a result of the building lifecycle CO_2 assessment for the flat type, compared with case 1, case 2 decreased by 1.0%, case 3 by 4.5%, and case 4 by 5.4%. For the tower type, compared with case 1, cases 2, 3, and 4 decreased by 1.3%, 4.9%, and 5.5%, respectively.
3. Such decreases occurred because the quantities of materials like concrete and rebar per unit area of cases 2, 3, and 4 were decreased compared with case 1 by increasing the use of plaster board drywall for the existing bearing wall, while simultaneously modifying the wall type structure of case 1 to a column type structure gradually in cases 2, 3, and 4.
4. As a result of the lifecycle cost of the flat-type building, compared with case 1, cases 2, 3, and 4 showed decreases of −0.01%, 5.8%, and 5.9%, respectively. With the tower type building, compared with case 1, cases 2, 3, and 4 showed decreases of 1.1%, 3.3%, and 3.5%, respectively.
5. As described for the CO_2 reduction effects, such decreases in the costs of cases 2, 3, and 4 compared with case 1 are attributed to modifications of the concrete wall to a column type flat slab structure; thus, the construction periods decreased.

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